

N 66 11771

20

FACILITY FORM 602

(ACCESSION NUMBER)

34

(PAGES)

OR 67973

(NASA CR OR TMX OR AD NUMBER)

(THRU)

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(CODE)

30

(CATEGORY)

GPO PRICE \$

CFSTI PRICE(S) \$

Hard copy (HC) 2.00

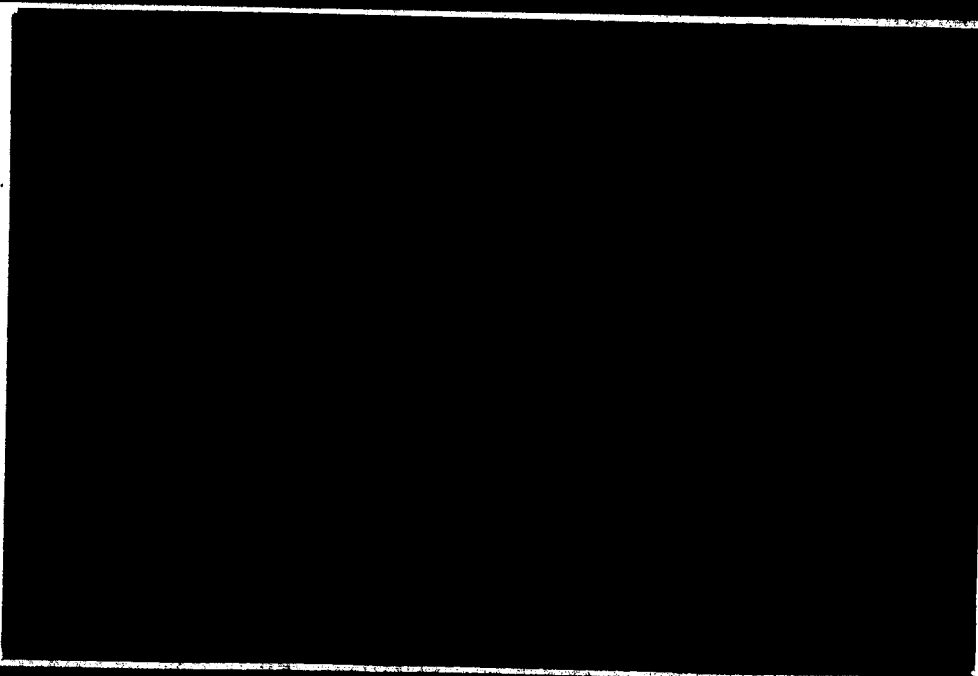
Microfiche (MF) .50

ff 653 July 65

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Center for Radiophysics and Space Research

ITHACA, N. Y.



Center for Radiophysics and Space Research
Cornell University
Ithaca, New York

June 1965

CRSR 198

OPTICAL PROPERTIES OF THE MOON'S SURFACE^{*}

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^{*}
(Paper presented at the Conference on the Nature of the Surface of the Moon, Goddard Space Flight Center, Greenbelt, Maryland, April, 1965)

I would like to discuss the optical properties of the moon's surface and what can be deduced concerning the outermost millimeter or so of the lunar surface when these properties are combined with appropriate laboratory studies. I believe that the optical evidence gives very strong indications that the lunar surface is indeed covered with a layer of fine dust of unknown thickness.

The moon's surface is characterized by a number of rather unusual optical properties, which are summarized in Figure 1. The brightness peaks at full moon, when the source is directly behind the observer, that is, when the sun is directly behind the earth. The brightness decreases sharply as the phase angle increases from zero degrees, and this is true no matter what part of the lunar disk one is observing. The upper part of Figure 1 gives two typical curves illustrating how the brightness of two areas vary as the angle of incidence i changes. The upper left curve is for an area on the 0° meridian of longitude, ϵ being the angle of observation. The upper right curve corresponds to an area on the 60° meridian of longitude as the angle of incidence changes. The shape of the curves is apparently pretty much independent of latitude; one gets a similar sort of photometric function for any lunar latitude as long as the longitude remains the same. There is some scatter about these mean curves for various areas on the lunar surface, but the departures from the mean curves are not nearly as significant as the range of values which the reflection law for a variety of different kinds

of surfaces can take.

In the lower left of Figure 1 are shown curves of polarization as a function of phase angle ϕ . The shape of the curve is very nearly independent of position on the lunar surface. The polarization is negative for phase angles less than about 23° , and goes through a negative maximum of about 1.0%. Then at 23° or so, the polarization becomes zero and the plane of polarization rotates 90° . The polarization then goes through a positive maximum, when the phase angle is around 90° to 110° , depending on the area looked at. The brighter areas, such as the highlands, generally have lower positive polarization and the darker areas, such as the maria, have higher polarization. The position of the maximum may be shifted a little bit toward larger phase angles for the darker areas.

The color of the moon is rather significant; the moon is redder than sunlight. The lower right part of Figure 1 shows color differences on a magnitude scale versus wavelength for various areas on the lunar surface. This data has been corrected to a color difference of zero at a wavelength of 5600° , which is the wavelength of the green filter we use.

It is convenient to characterize these photometric curves by a number of parameters. The first parameter is the normal albedo A_n , which is the brightness of the surface relative to the brightness of a perfectly reflecting, perfectly diffusing surface, both areas viewed and illuminated normally. The range of normal albedo on the moon is from five percent to about eighteen percent.

The shape of the backscatter curve can be characterized by the backscatter ratio, B_s , which is the ratio of the brightness at $\epsilon = 60^\circ$ and $i = 0^\circ$ to the ratio of the brightness at $\epsilon = 60^\circ$ and $i = 56^\circ$. These two points are shown in the upper right curve of Figure 1. The backscatter ratio for the moon is something like 0.34 to 0.48.

The polarization can be characterized by three parameters: the point of negative maximum, the inversion angle, and the point of the positive maximum. On the moon the negative maximum has the range of about 0.9% to 1.3%, the inversion angle from 22.5° to 23.5° ; the value of polarization at positive maximum ranges from about 5% to 17%, and the position of the positive maximum is 90° to 120° .

We measured the color of our laboratory surfaces at 4250 \AA , 5600 \AA , and 6450 \AA . B-G refers to the brightness of the surface at the position of the blue filter on a magnitude scale relative to the brightness at 5600 \AA ; and similarly for R - G, which refers to the red filter. Lunar values of B-G are from about +0.30 to +0.50; and of R-G are from -0.20 to -0.30.

The fact that every area on the lunar surface possesses these unusual optical characteristics shows that they must be exogenous and are not due to some peculiar property of lunar lavas or to some other internal cause. I suggested a couple of years ago that these rather remarkable lunar photometric properties could be explained as the result of micrometeorites impacting the lunar surface and pulverizing it to a very high

degree. The resulting dust would be acted upon by the solar wind to darken it and otherwise alter the optical characteristics. If this suggestion is correct, then if we take a rock of the proper composition, grind it up, and irradiate it with protons of a few kilovolts energy to simulate the solar wind hitting the moon, the resulting material should possess the proper photometric properties.

Figure 2 shows the photometric properties of hydrogen-ion-irradiated dunite powder. If the solar wind is impacting the moon at the same flux as measured by Mariner II, the radiation dose which this powder has received would be equivalent to something like 100,000 years on the moon. As you can see, the photometric properties of the dunite powder reproduce those of the moon quite well.

I would like to spend the remainder of the time discussing some of the properties of the surfaces which affect their photometric characteristics, whether one can deduce that other types of surfaces could not have these photometric properties, and also possibly say something about the composition of the lunar surface. This last objective is rather tentative at present. In the laboratory studies I am about to describe, I have been helped by Hsiu Yung Chow and Eddie Wells, who are graduate students at Cornell University.

Figure 3 is a schematic diagram of the process which I believe is responsible for the darkening of the lunar surface

by the solar wind. Ions from the solar wind impact the particles which make up the lunar surface and sputter atoms off of these particles. Assuming that the moon is composed of a silicate rock material, the sputtered atoms will consist of oxygen, silicon and various kinds of metals. Some of these sputtered atoms will leave the surface completely. However, when one has a rather complex surface, some of these sputtered atoms can fly over and stick to the undersides of adjacent rock particles. Because oxygen is a more volatile element it will have a lower sticking coefficient than the other types of atoms and fewer oxygen atoms will stay on the undersides of these particles than the silicon or metal atoms. This process results in a coating of a dark material on the underside of a rock particle; the coating is probably a nonstoichiometric silicate compound (or glass) which is deficient in oxygen.

The sputtering action of the solar wind, of course, will also make etch pits in the surfaces of the particles and it will generally clean up their upper surfaces. But the primary mechanism responsible for the darkening is the coating of the underside of the particles with a thin, highly absorbing, non-stoichiometric compound. Lattice vacancies in such compounds would be highly efficient in producing absorbing effects.

Figure 4 shows an experiment we did in the laboratory. We took an aluminum oxide ball and put it inside an aluminum oxide crucible and bombarded it with 2 kev He ions from above. The

middle photo shows the bombarded ball and the unirradiated ball. You can see that the unirradiated ball is shiny and that the upper surface of the irradiated ball has been cleaned and roughened by sputtering but that the undersurface is darkened. The right hand photo is a photomicrograph of the interface between the dark and light areas of the irradiated ball. Where there are little asperities sticking out from the ball, a dark streak was formed under the asperity. This streak is the geometric shadow of the asperity to the ion beam.

Figure 5 shows how the ion bombardment affects the photometric properties of some large-sized materials: rocks and chunks of rocks. As you could see from Figure 3, the darkening is much more efficient on a rough surface than on a smooth surface.

On many of the following slides you will see a white disk on a black square; this is to give you an albedo reference. The dark square is black velvet and has an albedo of about one percent; the disk is magnesium oxide powder and has an albedo close to unity.

Figure 6 is a photo of some coarse olivine basalt powders. It shows the effect of particle size and the effect of different types of irradiation on the appearance of a rock powder. The top row is the unirradiated material. The middle row is after 10^6 roentgens of gamma ray irradiation from Co^{60} . The bottom row is after hydrogen ion irradiation. You can see that the

gamma radiation had no effect at all. It obviously didn't affect the color or the albedo or the other photometric properties appreciably, either. Hydrogen ion radiation is very efficient for changing the photometric properties. The coarser materials darken less than the finer materials.

You can understand how finer particles are much more efficiently darkened than coarser particles by the mechanism which I showed in Figure 3 just because there are so many more free surfaces. All naturally occurring rocks and minerals are partially absorbing. Large particles, whether or not they are bombarded, have their optical properties dominated by the absorbing and reflection properties of the rock itself. But when finely ground, the particles become translucent, and if an absorbing coating is put on the undersides, the optical properties are now controlled by the coating, rather than by the optical properties of the rock itself.

Figure 7 is a photo of fine olivine basalt powders. These have been handled somewhat before the picture was taken. When we first took them out of the vacuum system, they were quite uniformly darkened. Again the gamma irradiation had no effect all. Hydrogen ion bombardment had a remarkable effect. Also shown is a sample which we bombarded with helium ions. The effect of helium ion irradiation is about the same as hydrogen ion irradiation, except the efficiency is better. The same dose of helium ions will produce the same effects in a much shorter time

than an equivalent dose of hydrogen ions.

Before we proceed it is important to show that the darkening effects of ion irradiation is not due to cracked pump oil or to some other spurious effect. We have several independent indications that the effects are real, but the most dramatic proof is shown in Figure 8.

The materials in each row of Fig. 8 were irradiated simultaneously, side by side in the vacuum system. The top row is untreated material; the center row was irradiated by hydrogen ions; the lower row by helium ions. The powders are pure magnesium oxide, aluminum oxide, and silicon dioxide, plus mixtures of these three powders. The mixtures are physical only and are not chemically combined. I draw your attention to the two mixtures of SiO_2 with Al_2O_3 and with MgO , both of which darkened appreciably under hydrogen ion irradiation, whereas the pure materials darkened only very slightly. This figure illustrates the non-linear effect, so to speak, of the ion irradiation, in that one cannot deduce from bombarding pure materials what the optical properties of a mixture of materials would be. Bombardment by helium ions darkened all the powders quite a bit with the exception of the magnesium oxide which darkened very little. Even so, the mixtures have a lower reflectivity than the pure materials.

This figure also illustrates that the SiO_2 lattice has a rather strong role to play in this phenomenon because the mixture

of the aluminum oxide and magnesium oxide did not darken nearly as much as the mixtures which contained the silicon dioxide.

Figure 9 shows some pure metal oxides which we bombarded. The ferric oxide was darkened in both cases by both hydrogen and helium ion irradiation to about the same extent. Hydrogen ion irradiation reduced cupric oxide to pure metal but helium ion irradiation did not greatly affect it. This illustrates that, particularly in the case of copper oxide, there evidently are some chemical effects occurring which are important for certain pure materials as well as just the mechanical effects of sputtering. The other oxides were affected only slightly by irradiation.

Figure 10 shows some rock-forming mineral powders before and after hydrogen irradiation. Quartz is not changed much. There is a strong correlation between composition and the amount of darkening. Basic materials generally turn darker than acidic materials and are bluer.

Figure 11 also illustrates the effect of composition. In this figure is shown enstatite, which is mainly magnesium silicate, and hypersthene, in which some of the magnesium atoms are replaced by iron. The hypersthene is darker than the enstatite; it is also bluer. In other words, the iron content has an effect on the optical properties of an irradiated mineral. I think that this has something to do with the fact that iron is a transition metal and itself forms nonstoichiometric compounds.

In Figure 12 are shown some igneous rock powders which we irradiated. Again the effect of composition is striking; the basic materials are generally darkened and less red than the acidic materials. I would draw your attention to the irradiated chondrite. Note that it is much darker than any of the igneous rocks.

Figure 13 gives the effect of particle size on the quantitative photometric properties of olivine basalt powder. These are the photometric characteristics which were defined in connection with Figure 1. The gray bands on all the curves are the range of lunar values.

The normal albedo of the unirradiated material increases as the particle size decreases, but for the irradiated material the albedo is roughly constant. The backscatter ratio decreases drastically with particle size. The amount of positive polarization is a strong function of particle size and decreases in a very striking manner as one goes to smaller particles. For large-sized materials the polarization is far too big for the moon. For large particles the phase angle of the positive polarization peak is shifted to much higher values than is true for the moon. In our apparatus we can only measure up to a maximum phase angle of 130° and the ρ_+ curve is still rising at 130° for the particles which I have labeled with an arrow. Thus the polarization provides another indication that large chunks of material are not exposed at the lunar surface. This was emphasized quite a while ago by Dollfus.

The material which has been labeled as being one centimeter in size on the figure actually refers to the freshly-broken surface of solid rock and is not pulverized material.

It is clear from this figure that only particles which are of the order of 1 to 10 microns in size can simultaneously reproduce all the lunar photometric characteristics. Now, it is possible to reproduce one or two of the lunar photometric properties in other ways. For instance, a high backscatter ratio can be obtained by using chunks of vesicular rock formed into a jumbled surface which is riddled with tunnels pointing in all directions. However, in general, such large chunks will have a high polarization, far too high for the moon, and the phase angle of the maximum polarization has too large a value. Also, Lyot and Dollfus in their investigations found that certain varieties of volcanic ash would have the correct polarization curves; but these ashes do not have the correct brightness functions.

It may be inferred that the size distribution of particles composing the lunar soil peaks somewhere between 1 and 10 μ .

Figure 14 shows the effect of radiation dose on the photometric properties of olivine basalt powder. All the curves saturate in a time which is of the order of a hundred thousand years or so on the moon. On this slide I have also shown the effect of gamma ray irradiation; the optical properties of material

treated with gamma rays is virtually the same as for the unirradiated material.

The effect of helium ion irradiation to a dose of about 88 coulombs/cm² is pretty much the same as a three to five times larger dose of hydrogen ion irradiation.

On the basis of these curves, it is reasonable to state that the average particle has been exposed on the lunar surface for a time which is of the order of a hundred-thousand or a million years. This is much less than any estimates of the ages of most features on the lunar surface.

After prolonged irradiation the albedo of most rock powders actually gets lower than the lunar surface albedo. Hence, one must think that there is some agent which is counter-acting this darkening process. We put some irradiated rock powder in a vacuum furnace and heated it up to 450°C and held it there for over a day. There was no appreciable change in the photometric properties. These coatings appear to be quite stable.

I think a reasonable explanation for the higher lunar albedo is that micrometeorites are continually stirring up the surface and exposing undarkened materials. At all times one sees a mixture of darkened material and undarkened material such that the average particle has been exposed on the lunar surface for something like a hundred thousand years.

We also investigated the effect of porosity of the surface. We took the same powder and formed surfaces by pressing, pouring, and sieving the powder in order to see the effect of compaction

on the photometric properties. In the case of both the pressed and the sieved material, the photometric peak is wider than that of the moon, but for different reasons. Only the poured material gave the correctly-shaped backscatter peak. The pressed powder does not have a sufficiently complex and open structure to backscatter well. The sieved powder has the requisite complex structure, but even after irradiation the particles are somewhat translucent. In a loose structure light can shine through the particles and the powder will appear too bright at large phase angles. When a powder is poured, the particles form clumps which are sufficiently complex to backscatter well, but which will also block some of the transmitted light. Surfaces with the correct optical properties can be made by pouring the powder in a vacuum as well as in air.

Apparently the lunar surface is not porous to the extreme extent that Hugh Van Horn and I suggested previously. The surface does not have the extremely under-dense fairy castle structure, but rather consists of loose clumps of fine particles which themselves are quite complex and are capable of backscattering strongly, but the porosity instead of being something like 90%, which would be the case for the fairy castle structure, is about 80%. This is still quite under-dense. The powder is very compressive. It has the consistency of something like baking flour. I would imagine that if there were even a few feet of the stuff, an astronaut would sink into it up to his

knees and would have quite a time churning his way through. The dust would stick to him and is liable to be quite a nuisance in a number of ways. I imagine that on the moon anything which is a nuisance is dangerous.

Fig. 15 shows the effect of chemical composition on the photometric characteristics of rock powders. In all cases, the effect of irradiation is to bring the photometric properties close to those of the Moon. The backscatter ratio of the irradiated powder shown here is a little bit high. However, in this experiment we weren't so much interested in duplicating lunar photometric properties as in investigating the effect of composition on the photometric properties, so we were more interested in uniformity of the samples. As you saw in Figure 2 the backscatter ratio can be reduced by a proper preparation of the surface, at least for basic rock powders.

Most rocks when ground into a fine particle size are relatively colorless, so that their color indices are quite low. Only after irradiation does the color move toward the lunar values. The general tendency of the effect of irradiation is to redden rock particles. Evidently the dark compounds which coat these particles absorb more heavily in the blue than in the red.

There are a few remarks that one can make about the effect of composition. As one goes from an acidic to basic material the albedo of the irradiated powder decreases. There is a slight

tendency for the backscatter ratio to decrease. The polarization maximum tends to increase, and this is directly connected with the decrease in albedo. The polarization is dependent on two things: it depends on the light which is reflected from the surface of the particles, which is positively polarized, and on the light which is refracted through the particles, which is negatively polarized and which tends to cancel out some of the positive polarization. As the material is darkened and made more absorbing, some of the refracted, negatively-polarized light is cut out and the positive polarization is enhanced. Roughly speaking, irradiated acidic materials are redder than the basic materials, especially their blue-green index. However, there is not much variation in the red-green index. These are rough trends, but one can get departures from these trends.

Now, I draw your attention to the powdered chondrite shown at the extreme right of Figure 15. This is a sample of Plainview (a bronzite chondrite) after receiving the same amount of irradiation as the rest of the rocks. Its albedo dropped far below that of the lunar surface. The polarization positive maximum was way up to 43%. The negative minimum dropped down to 25%. The colors remained much bluer than the moon. There may be some indication here that at least chondritic meteorites do not come from the moon. One might try to say that perhaps the flux of micrometeorites at the lunar surface which is stirring up the material is bigger than we think it is so that the average

particle is irradiated just very slightly. This would tend to keep most of the optical properties of the chondrite within the range of lunar values except for the red minus green index, which would stay too low.

The primary reason for the photometric properties of the chondrite being different from those of igneous rocks is due to the high metallic iron content of the meteorites. Adding 15% by weight of metallic iron to any rock has the effect of increasing the positive and negative polarizations and of decreasing the color, making the material much bluer.

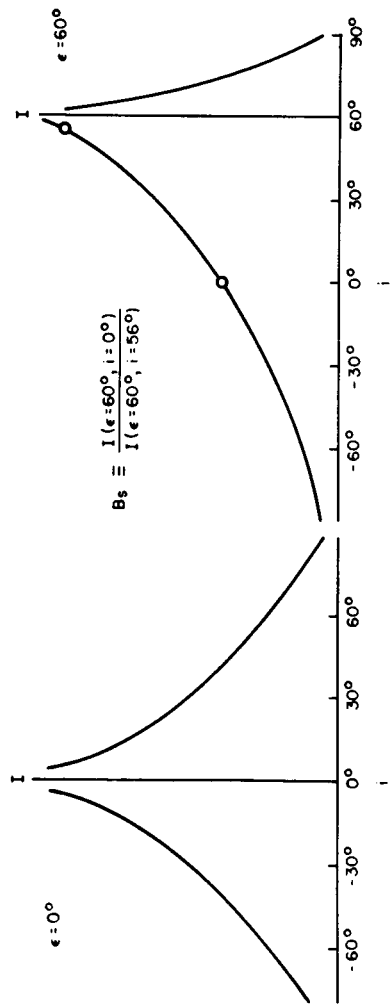
I would like finally to see if these studies can give any indication concerning the composition of the highlands and the maria. As you know, there are two theories. One says that the highlands are of different composition than the maria. Figure 15 is consistent with the highlands being more acidic than the maria.

The other theory, due to Gold, is that the material on the highlands contains a larger admixture of unirradiated material in the maria. That is to say, the material exposed on the surface of the maria is older on the average than the material covering the highlands. However, Figure 14 shows that all the photometric properties are monotonically changing functions of radiation dose. That is, as one increases the dose, the positive polarization rises, the negative polarization decreases, the color indices all change monotonically, and so on.

Thus, if the only effect were one of exposure age, then we would expect that the differences in photometric properties of the highlands and the maria would always be in the same direction everywhere on the moon. It is known that this is not always the case. As far as I know, there is no correlation between, for instance, the amount of negative polarization and the albedo, although there is a correlation between positive polarization and albedo. In general, the maria tend to be somewhat bluer than the highlands; this is just the opposite from what would be expected of igneous rocks, which tend to get redder with increasing dose, rather than the other way around. However, this last argument is not a very strong one because igneous rocks which are rich in ferric oxides are initially red and become bluer under irradiation.

Nevertheless, I feel that there are some tentative indications here that the differences in the photometric properties of the light and dark areas of the moon are at least partly due to real differences in composition and not just to differences in exposure age.

This research has been sponsored by a grant from the National Aeronautics and Space Administration.



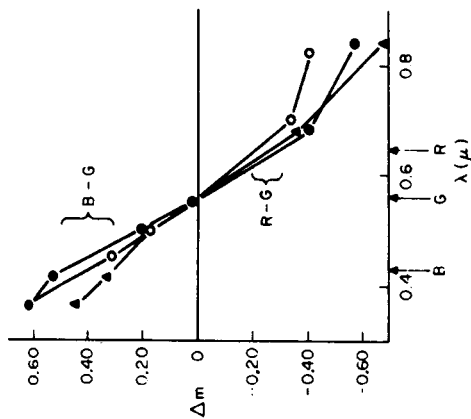
Range of Lunar Values

Normal Albedo : $A_n = 0.05 - 0.18$

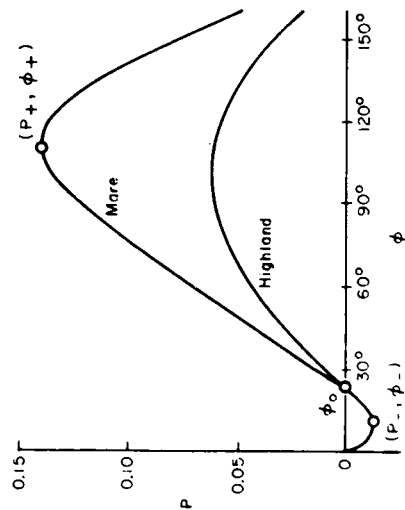
Backscatter Ratio : $B_s = 0.34 - 0.49$

Polarization : $P_- = -0.009 - (-0.013)$, $\phi_- = 10^\circ - 12^\circ$
 $P_+ = +0.05 - (+0.17)$, $\phi_+ = 22.6^\circ - 23.6^\circ$
 $\phi_0 = 90^\circ - 120^\circ$

Color : $B - G = +0.30 - (+0.50)$
 $R - G = -0.20 - (-0.30)$



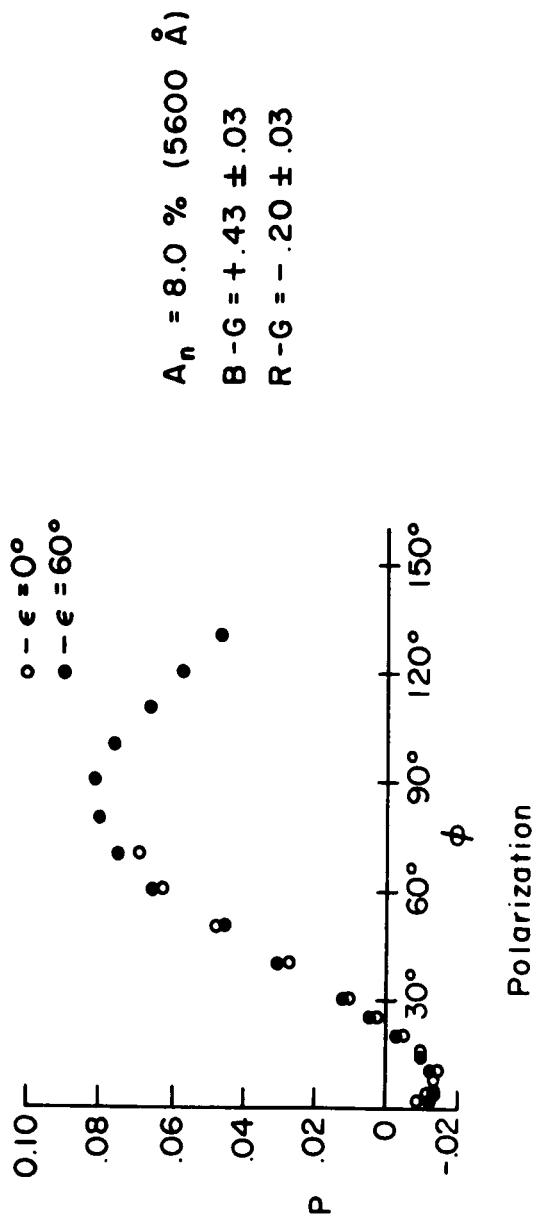
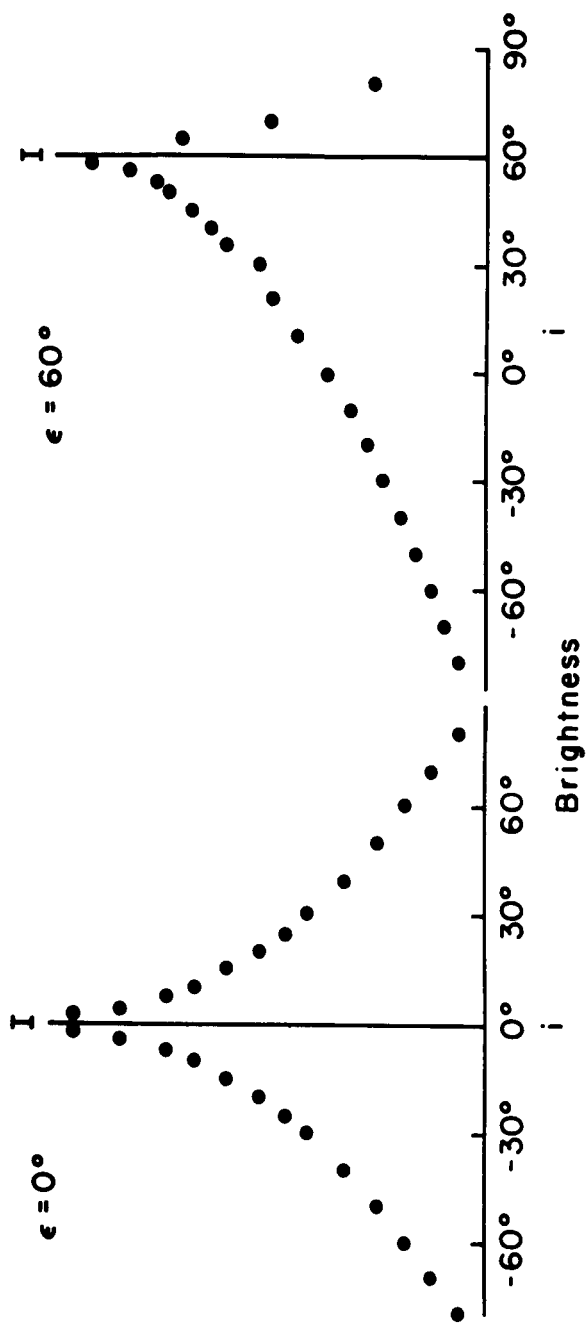
Color (corrected to 0.56μ)
 (Barabashev, Harris)



Polarization (Wright, Dollfus)

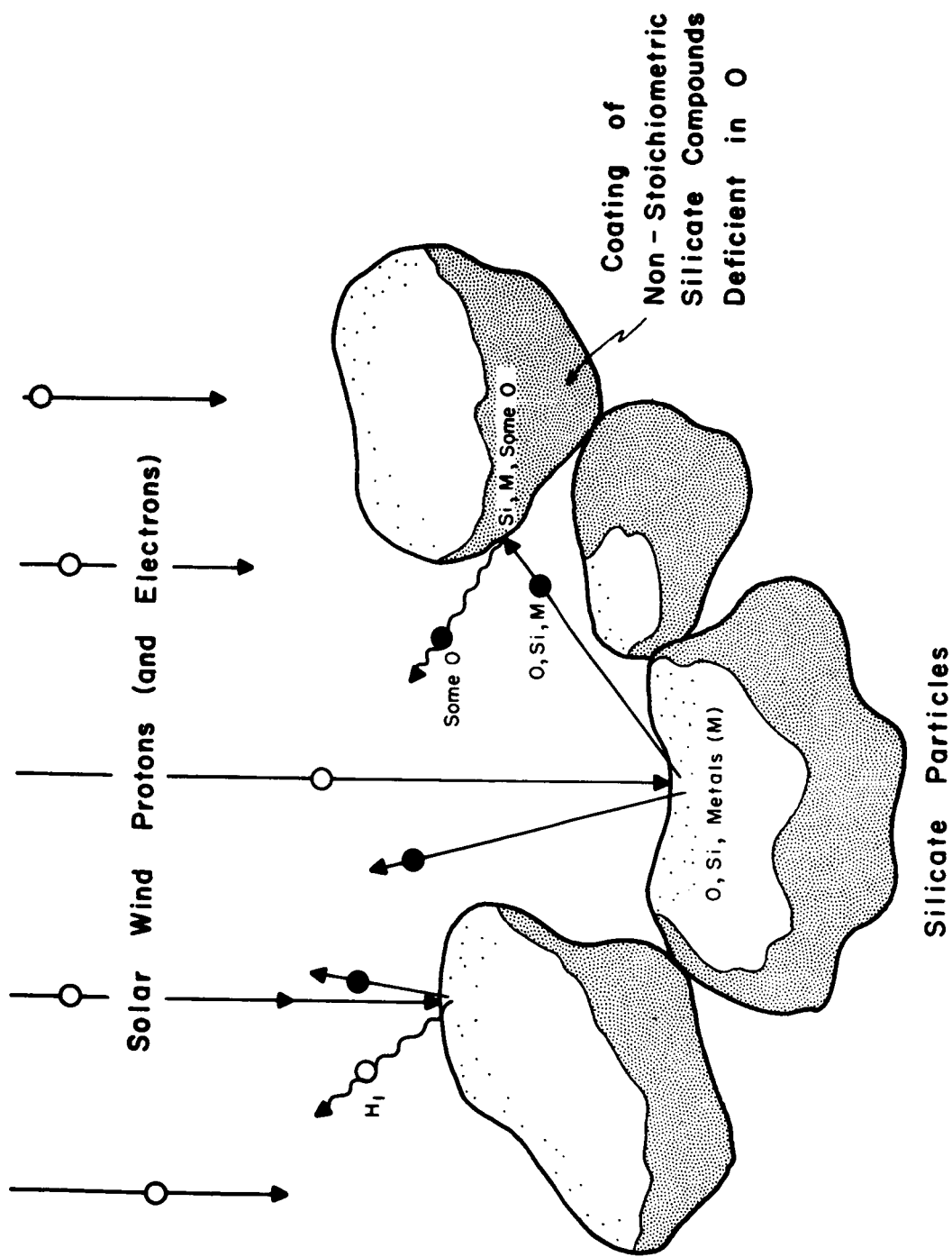
Photometric Characteristics of the Lunar Surface

Figure 1.



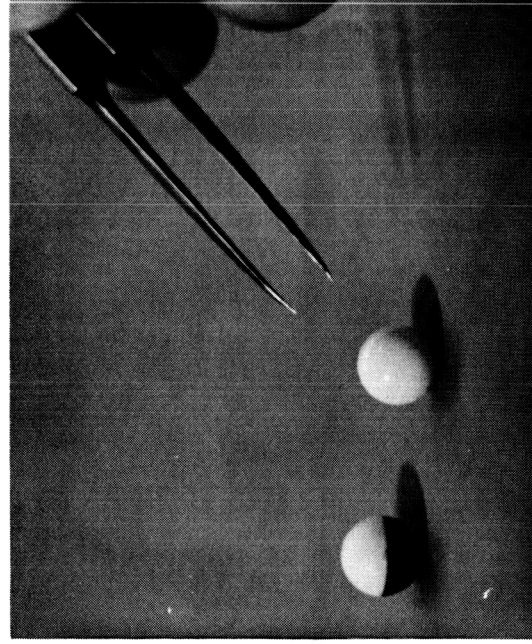
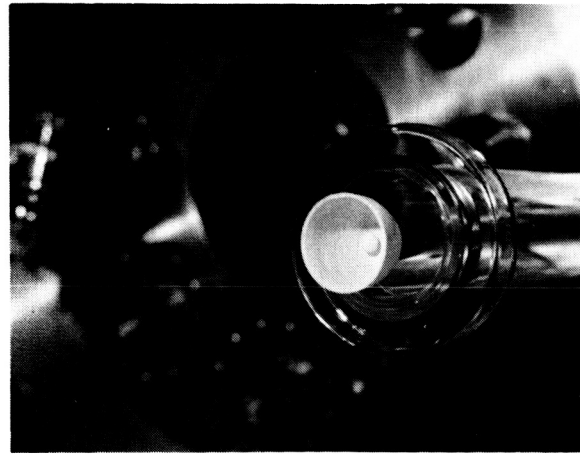
Photometric Properties of Dunite Powder
(Size $< 7\mu$) after 65 coul/cm² of H-Ion Irradiation

Figure 2.



Schematic Diagram of Process Responsible for Darkening of Lunar Surface by Solar Wind

Figure 3.



← 1 mm →

Al_2O_3 Ball Irradiated in Al_2O_3 Crucible by 2 Kev He - Ions

Dose = 90 coul/cm²

Figure 4.

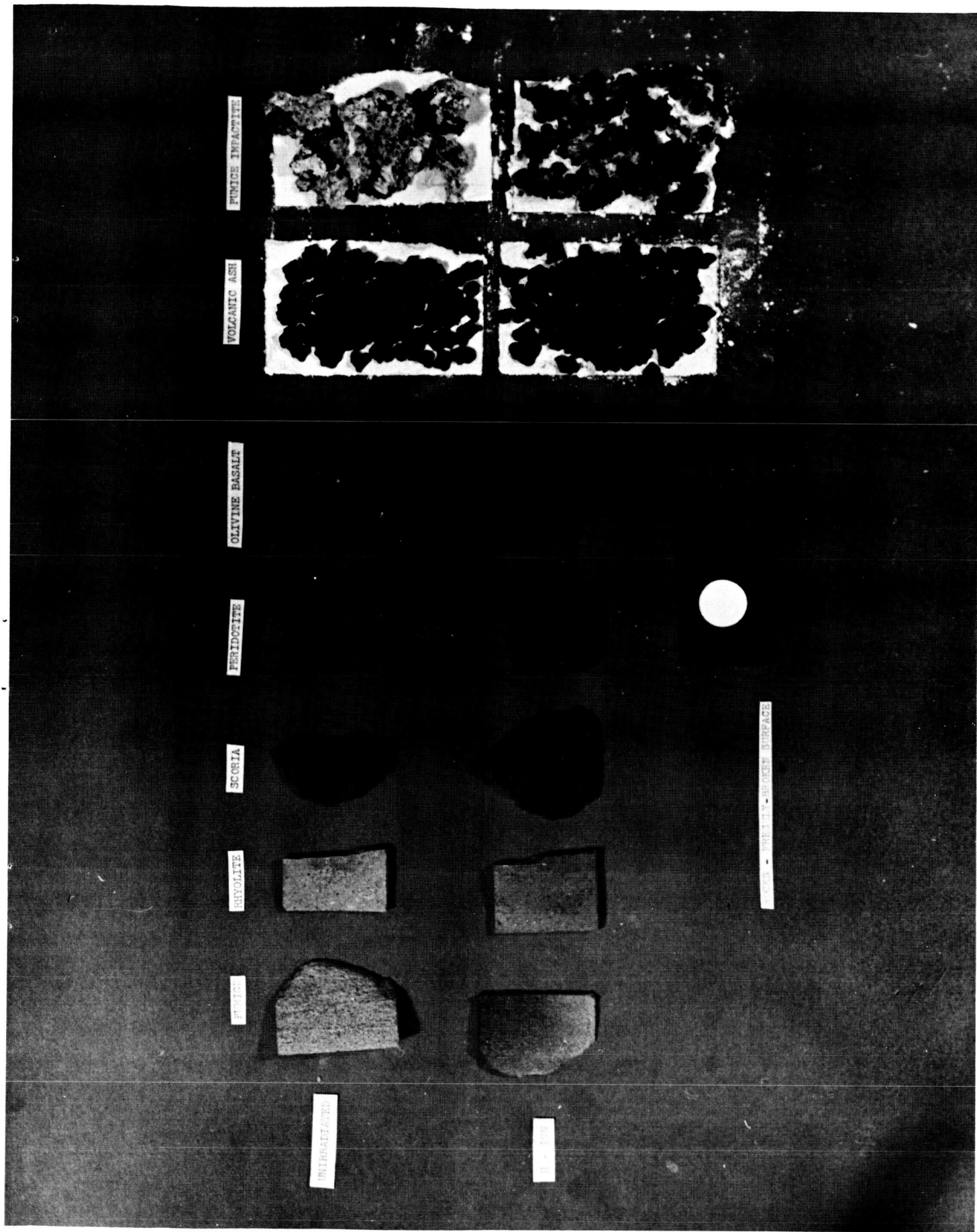


Figure 5.

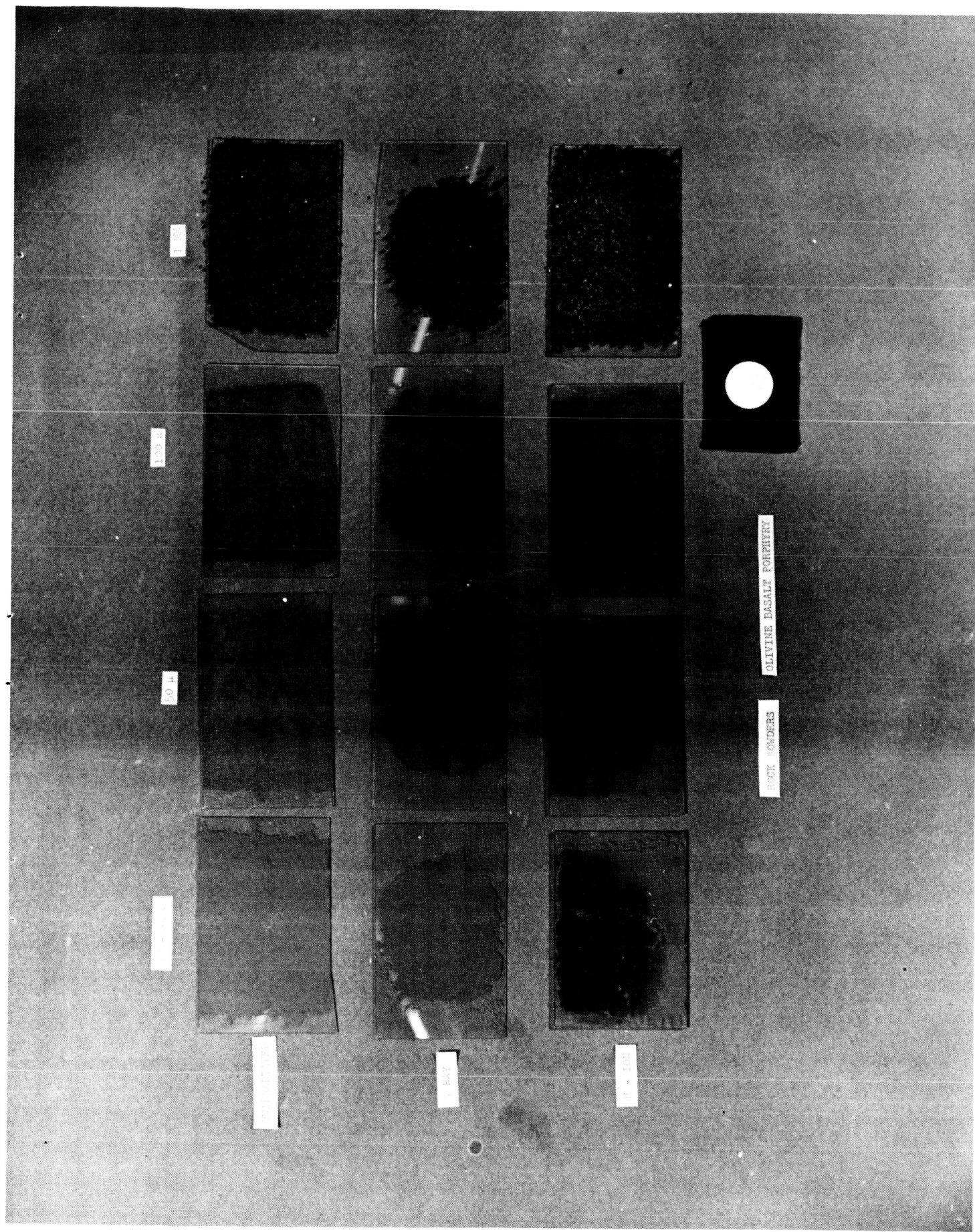


Figure 6.

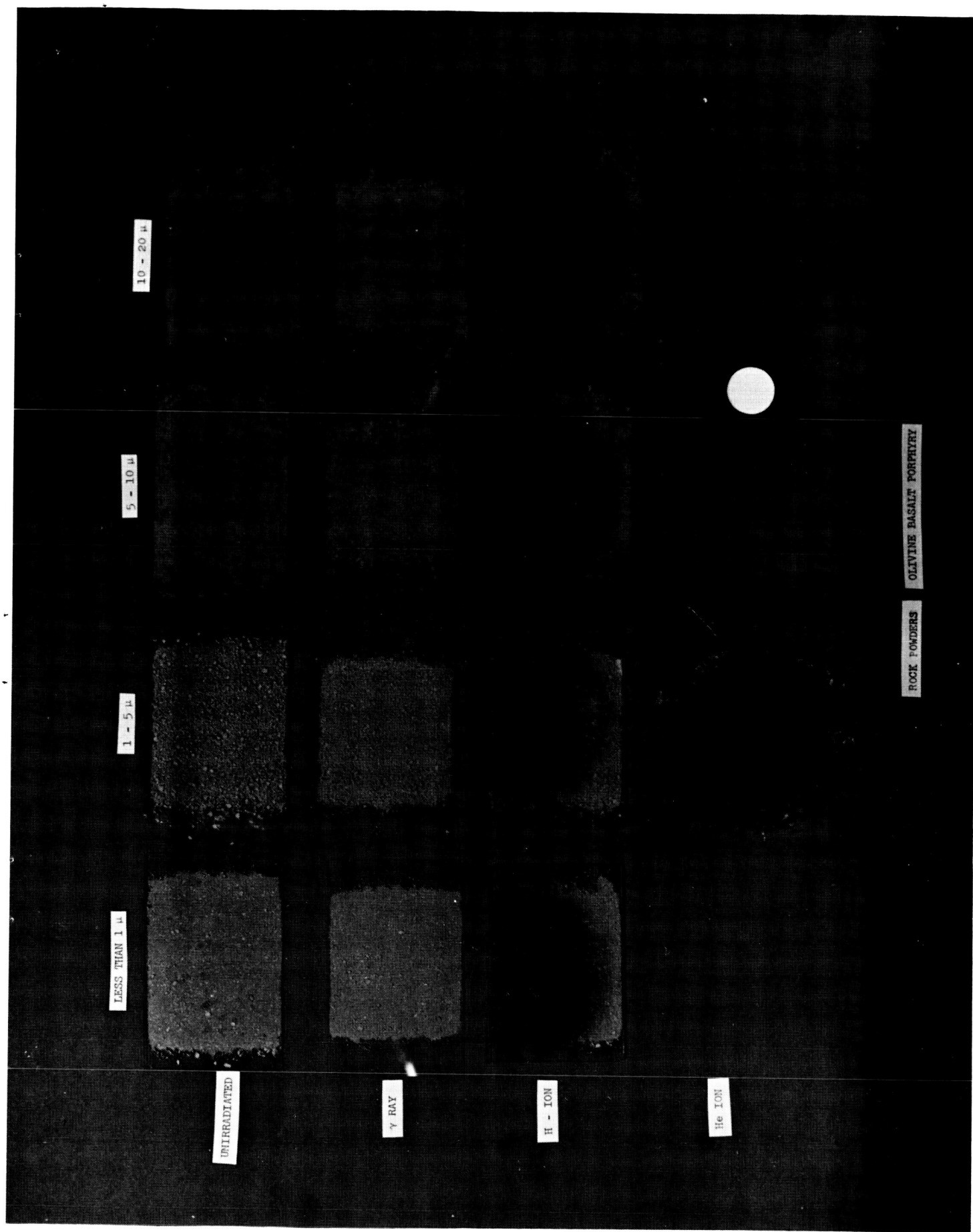


Figure 7.

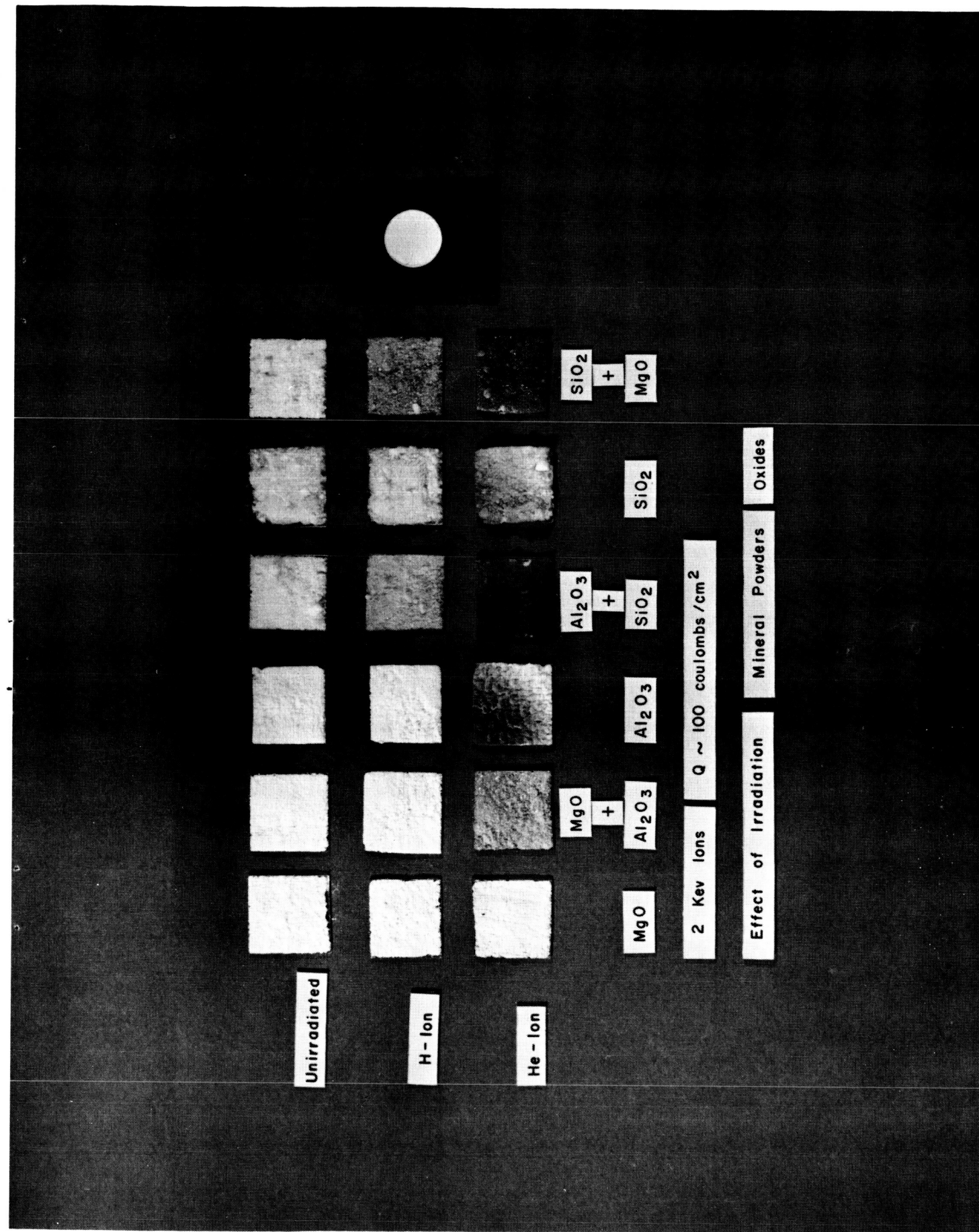


Figure 8.

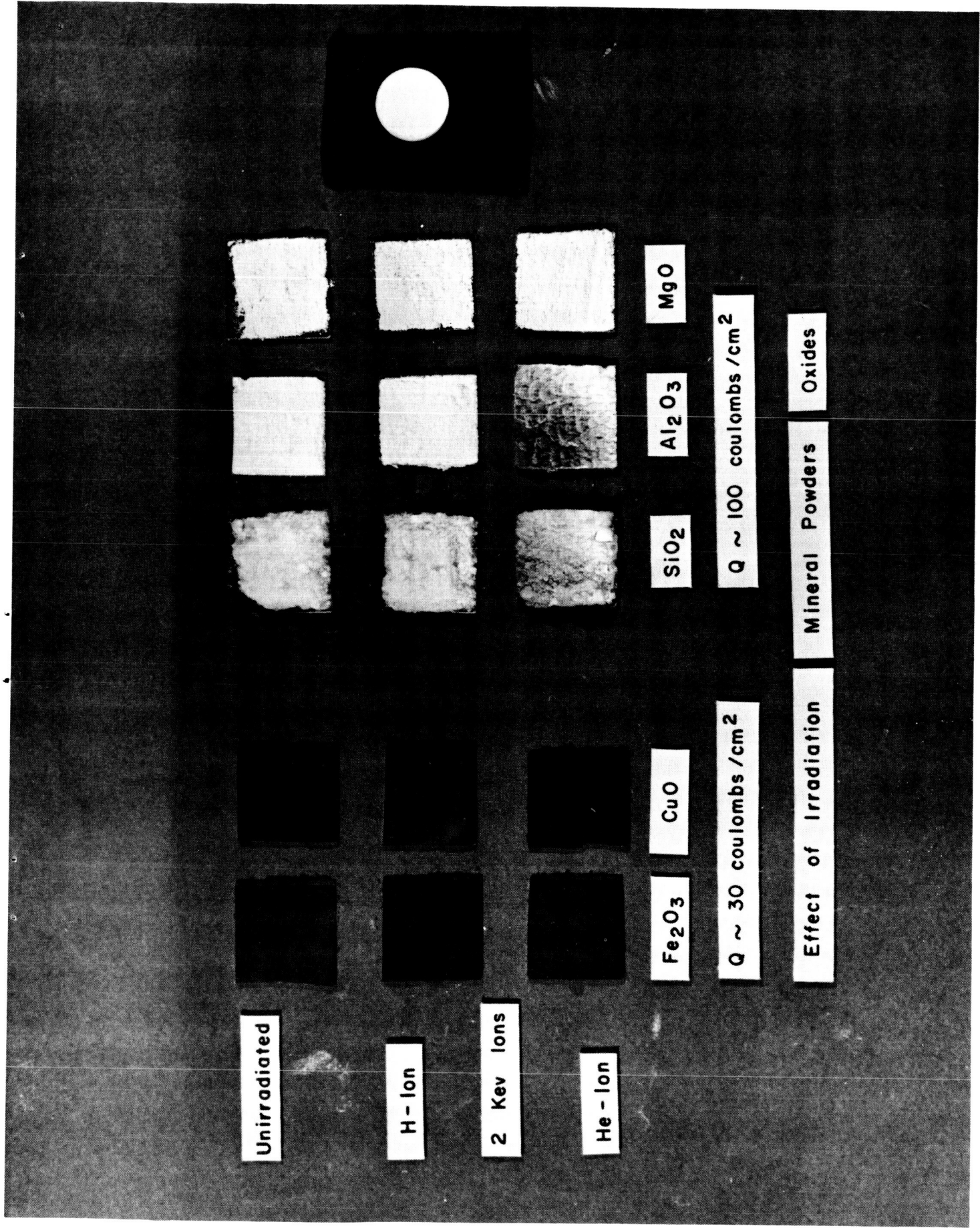


Figure 9.

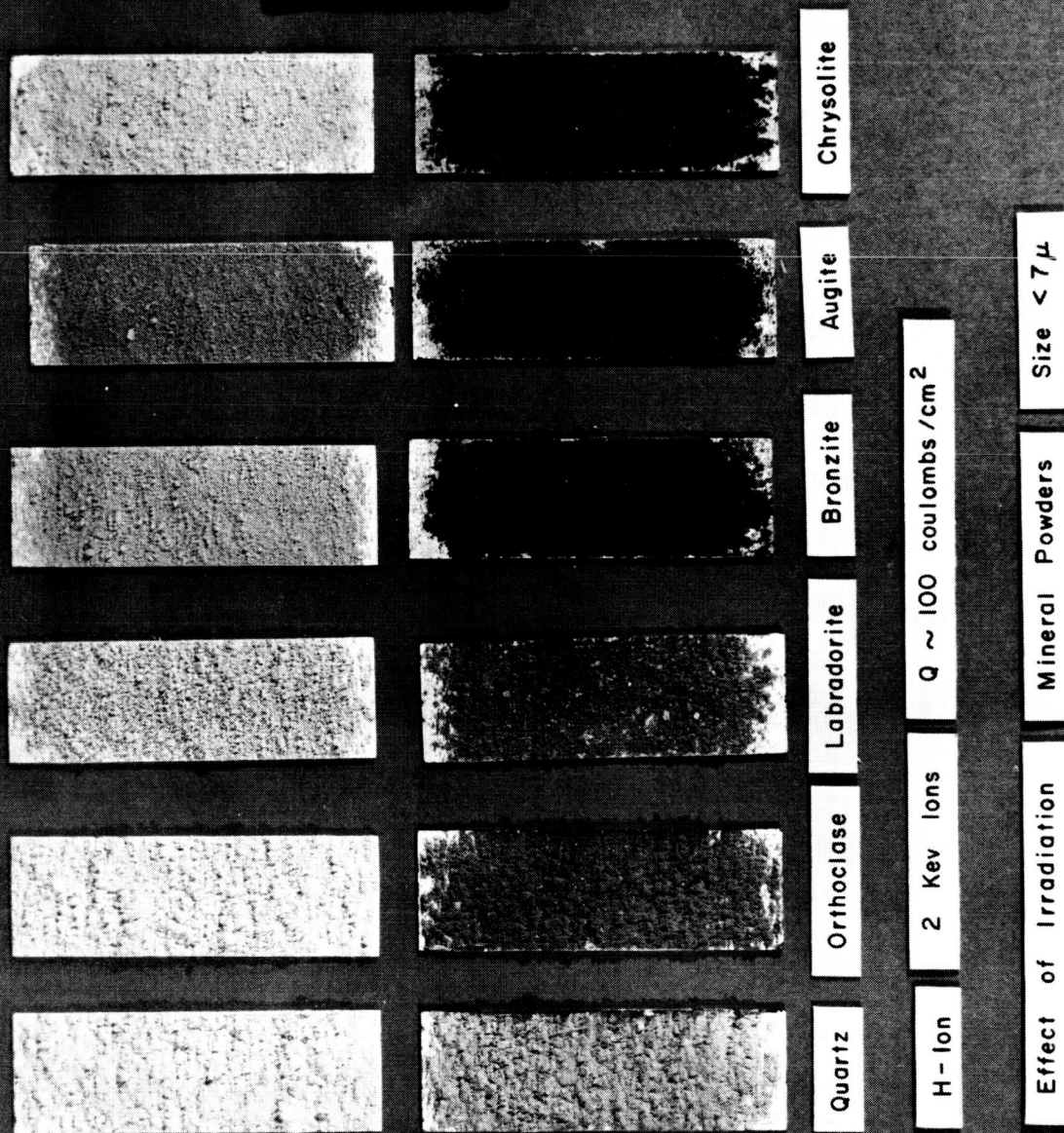


Figure 10.

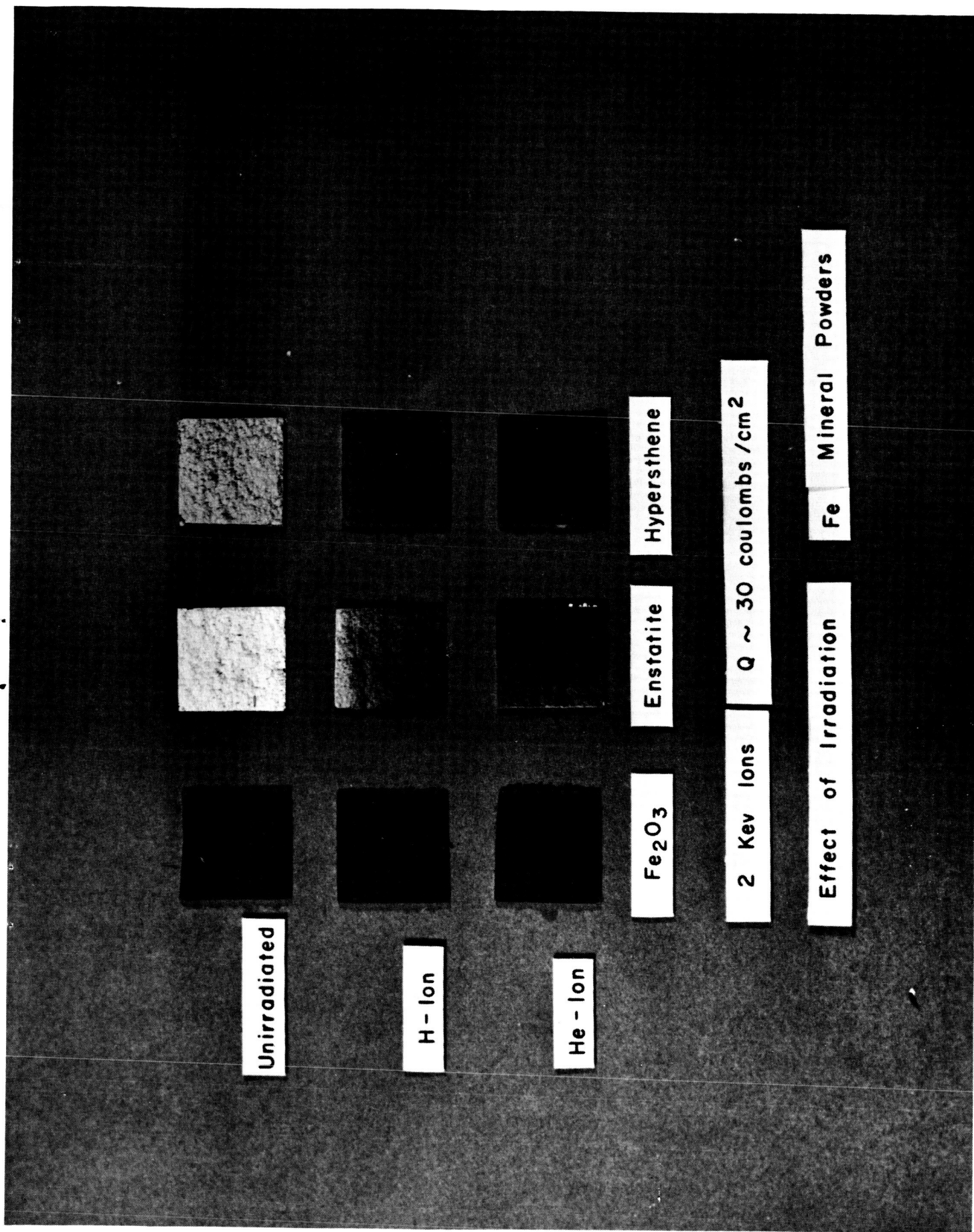


Figure 11.

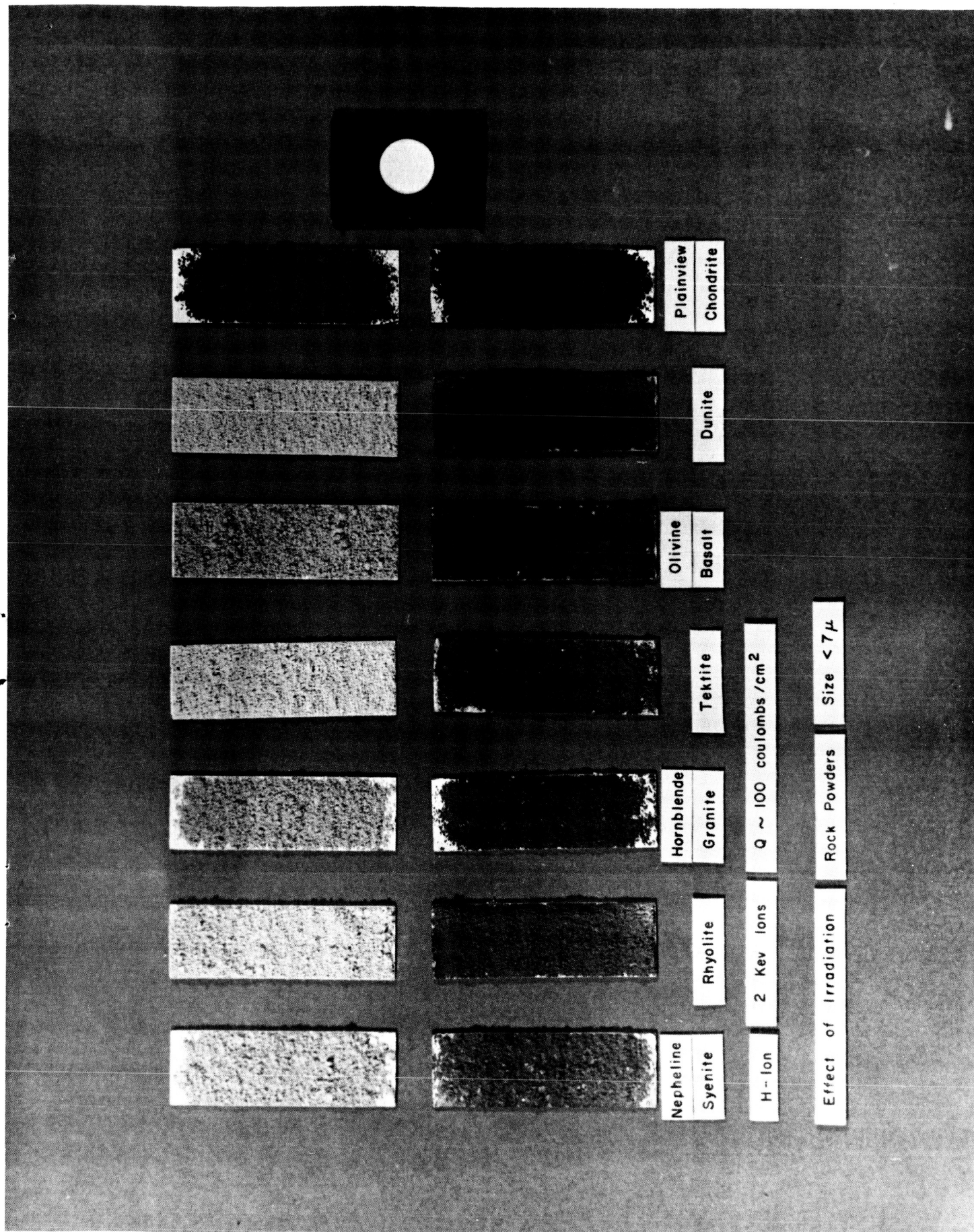
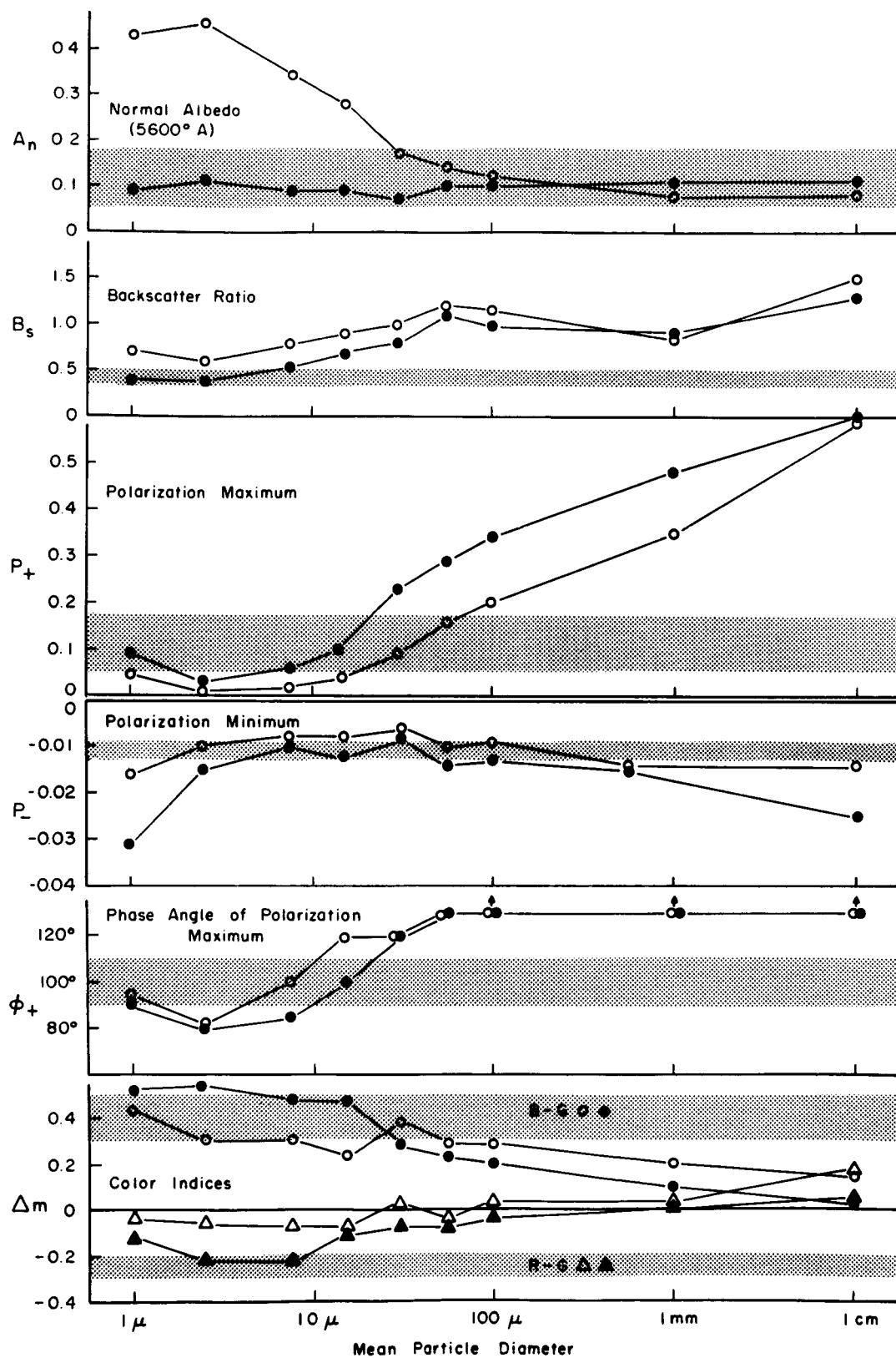


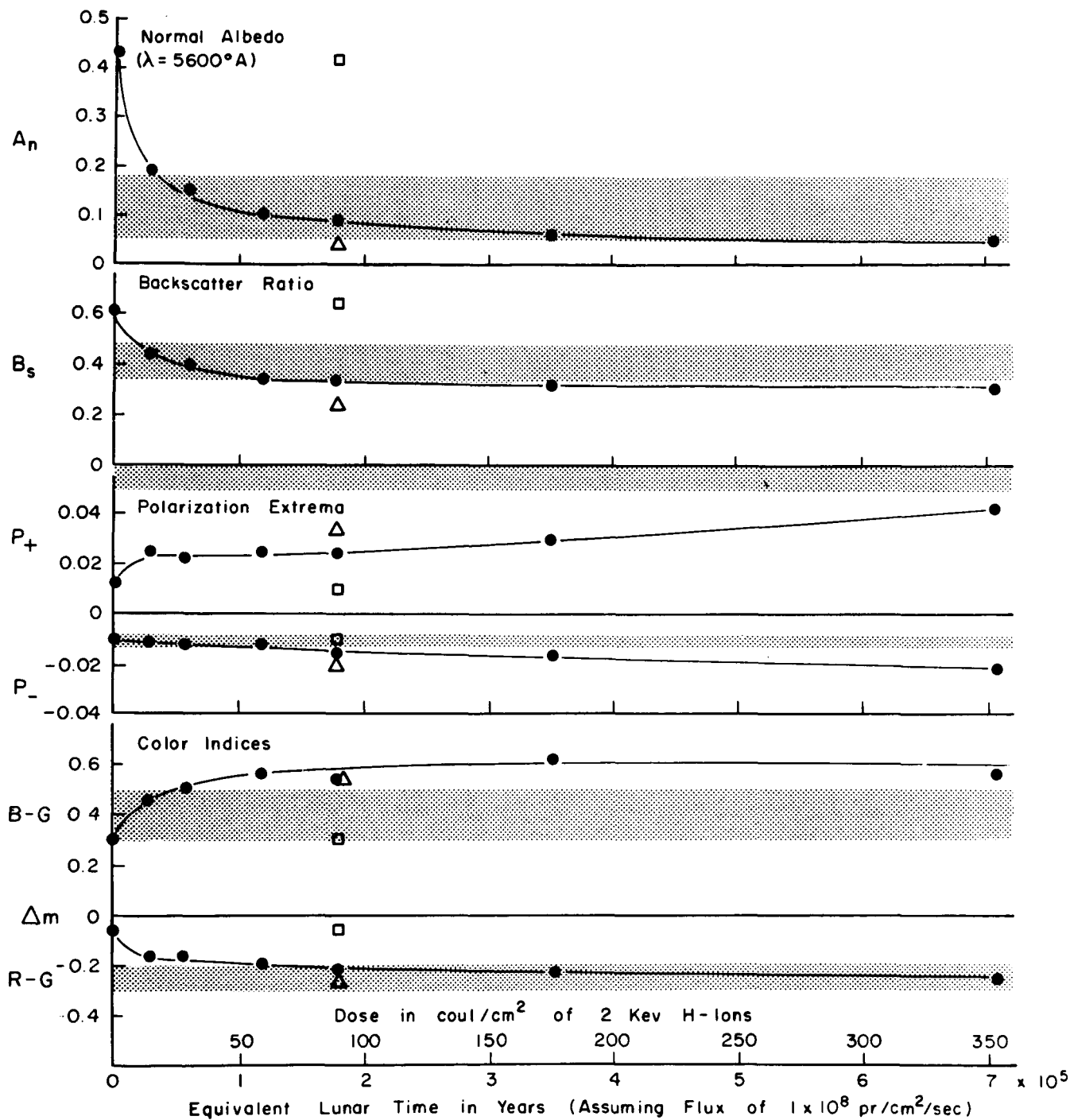
Figure 12.



Photometric Properties of Olivine Basalt Powders vs Particle Size

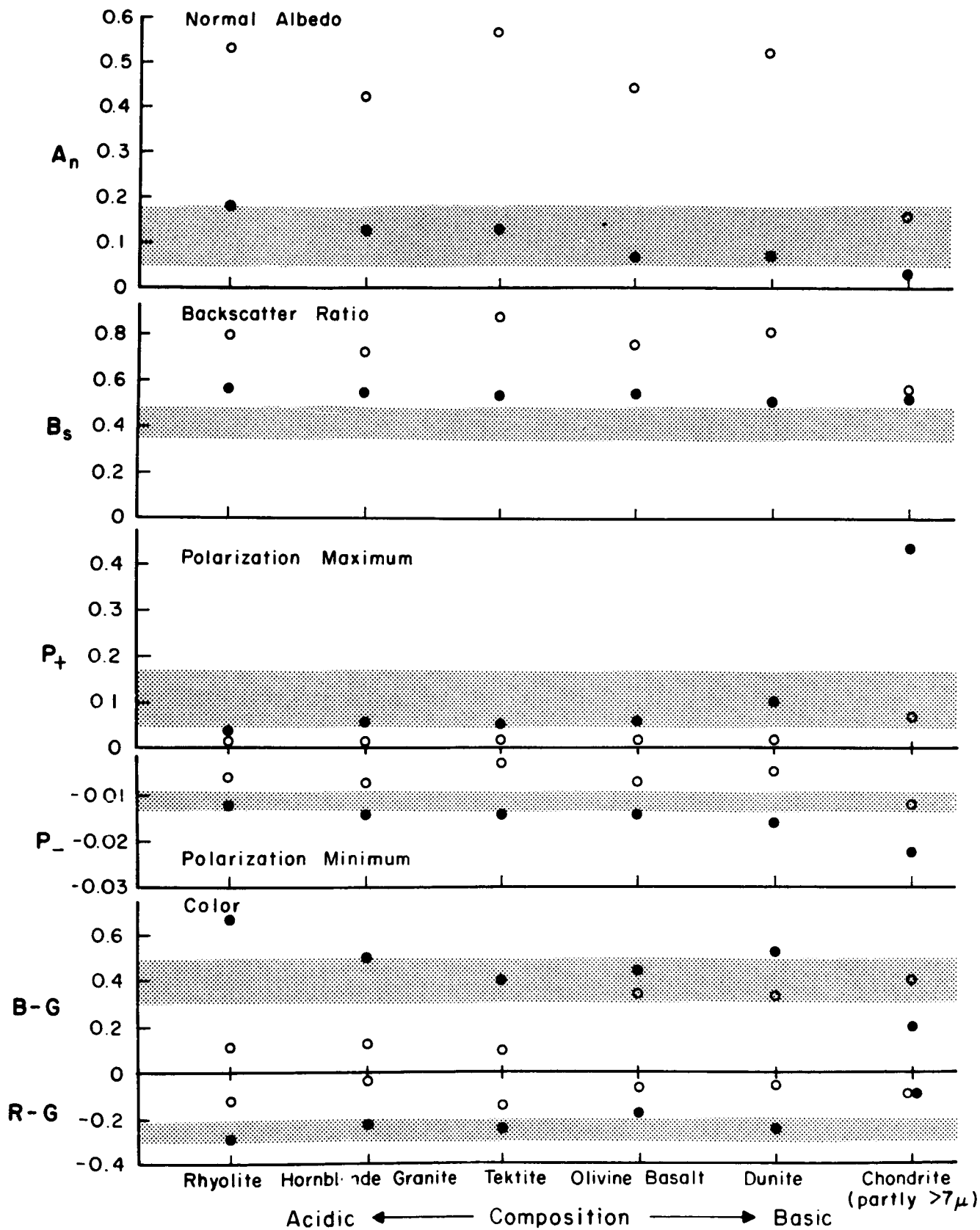
○ - Natural ● - After Irradiation by $90\ \text{coul/cm}^2$ of 2 Kev H-ion

Figure 13.



Photometric Properties of 1-5 μ Olivine Basalt Powders vs Irradiation Time
 ● - 2 Kev H-ions □ - γ -Rays : 10⁶ R from Co⁶⁰ Δ - He-ions : 88 coul/cm²

Figure 14.



Photometric Properties of Igneous Rock Powders (Size $<7\mu$)
 ○ - Unirradiated ● - After 88 coul/cm² of 2 Kev H-Ion Irradiation

Figure 15.